ARL-MR-0914 ● JAN 2016

US Army Research Laboratory

Visualization and Measurement of the Deflagration of JA2 Bonded to Various Metal Foils

by John J Ritter and Andrew R Demko

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14. ABSTRACT A series of experiments was conducted to better understand the mechanisms underlying the deflagration of nitrate ester-based propellants embedded with thermally conductive components. JA2 propellant was employed for the experiments. Strands were bonded on one side with an aluminum or copper foil, and their deflagration was videographically recorded. Foil thicknesses ranged from 1 to 3 mil. The data yielded measured values for 1) the JA2 stock's normal, linear-burning rate, 2) test-article burning rates relative to an axis parallel to their side wall, and 3) the angle between the burning surface and the side wall. The condensed-phase to gas-phase mass conversion rates for foil-bounded sections were up to 4 times higher than those for foil-less sections. The increases appear to be almost entirely due to increases in the area of the burning surface rather than an increase in the normal, linear-burning rate. It was also found that the pressure dependence of the gas-generation rates for foil-bounded sections was slightly less than that of foil-less sections. Because the test articles had a relatively simple geometry, the results should provide a good basis with which to validate computational fluid-dynamics models for simulating the deflagration of wire-embedded propellants.							
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1. Introduction

The US Army Research Laboratory (ARL) in collaboration with the Army Missile Research, Development, and Engineering Center (AMRDEC) is trying to enhance the gas-generation rates of minimum-smoke rocket propellant formulations without increasing their vulnerability to external threats. One approach is to embed propellants with thermally conductive wires. By enabling localized conductive heat transfer from the combustion zone into the uncombusted propellant,[1–7] the wires serve as an ignition source that creates conically shaped burning surfaces. Reported as early as 1955[8] and fielded in the 1960s (in Redeye and Stinger missile systems), this approach has not become a standard because it is difficult and costly to implement reliably. Two significant challenges are casting the propellant grains without breaking the wires and properly bonding the propellant to the wires such that there are no voids.

Given the challenges of reliably manufacturing wire-embedded propellant grains, performance increases need to be significant to justify any attempt at fielding the technology. However, the limited understanding of the phenomenon that exists today makes it hard to realize the technology's full potential. Only empirical models of the process have been developed to date, and they have not proven useful as design tools. There are numerous design parameters, including 1) the wires' thermophysical properties and diameter(s), 2) their quantity, spacing, and orientation within the grain, and 3) the thermophysical and chemical kinetics properties of the propellant formulation. Without a model capable of simulating the interplay between all of these parameters, grain optimization will be difficult to achieve.

Seeking insights into the phenomenon that will provide guidance, ARL is developing a computational fluid dynamics (CFD) model to simulate it.[9,10] As part of this effort, experimental data that can be employed for model validation were desired, with direct observation of burning surfaces produced by various propellant–thermally conductive material configurations being a specific interest. Results from prior experiments with wire-embedded JA2 propellant were previously published.[5] Unfortunately, the fine grid spacings required to model strands embedded with extremely thin (0.002–0.010-inch diameter) wires made them too computationally expensive to model.[10]

To produce results that could be directly compared to configurations that were practical to model, JA2 strands were configured with a 1-mil-thick aluminum (Al) foil bounding one side.[7] Giving a preliminary indication that the validity of the CFD model, additional validating data were sought. This report summarizes burning rates (BRs) produced when aluminum or copper (Cu) foils with thicknesses of 1–3 mils were bonded to one side of JA2 sheet stock.

2. Approach

2.1 Test-Article Fabrication

The propellant chosen for these experiments was JA2. This was done for several reasons:

- JA2 is composed of nitrocellulose, nitroglycerin, and diethylene glycol dinitrate. As such, it is chemically similar to minimum-smoke rocket propellants.
- ARL has developed a model with detailed gas-phase chemical kinetics that accurately reproduces the BR of JA2.[11,12]
- JA2 stock was readily available for use in preparing test articles.

Ideally the foil should be located inside the propellant sample; however, this proved difficult to implement reliably. Therefore, similar to the previous experiments, the test articles were made by bounding only one side of the JA2 sheet, creating a half sandwich. Figure 1 illustrates this setup.

The JA2 strands were prepared from 0.100-inch-thick sheet stock. Strands had a nominal width of 0.5 inch and a height of 2.0 inches. To them, the Al or Cu foil (or tape) was bonded. Foils (as opposed to tapes) were affixed by using a small amount of acetone to dissolve and subsequently cure the JA2 to the foil. Tapes had an acrylic-adhesive backing applied by the manufacturer. The conductive material, whether foil or tape, ran approximately ¾ the height of the sample. This configuration permitted BRs for foil-less and foil-bounded sections to be acquired from one test article. It was not necessary to use an inhibitor because edge effects did not present themselves as long as the strand had smooth surfaces and edges. Images of the burning event were obtained such that the 0.5-inch surface was facing the camera with the foil on the right edge.

The thicknesses and tape/foil configuration was dictated by commercial availability. Although an effort was made to obtain tapes/foils of each metal type that were comparable in thickness and adhesive type, there were differences. A 2-mil Al tape was obtained from McMaster-Carr (product No. 7925A1). It had a 2-mil-thick acrylic adhesive. A 3-mil Al tape was obtained from LaMart Corporation (product 213 Al tape). It had a 1-mil-thick acrylic adhesive. A 1.4-mil Cu tape was obtained from 3M (product 1181 tape). It had a 1.2-mil conductive acrylic adhesive. The 2- and 3-mil-thick Cu foils were obtained from McMaster-Carr (product Nos. 9053K312 and 9053K322, respectively).

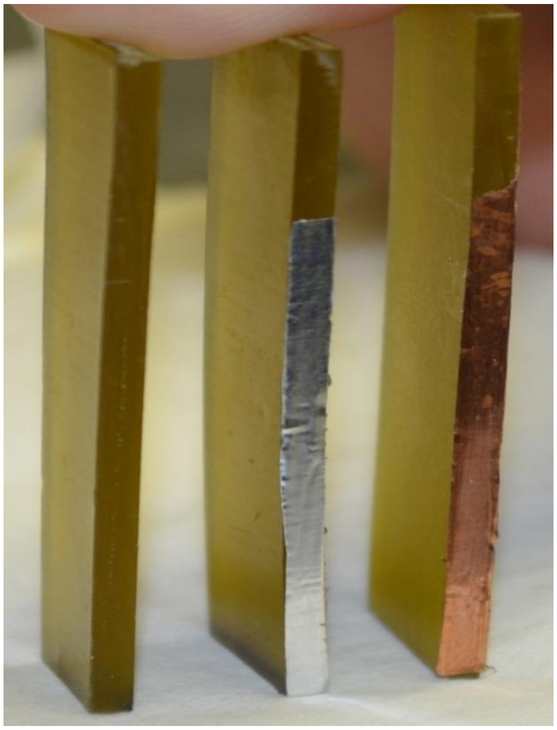

Fig. 1 JA2 samples (left to right) with no foil, Al foil, and Cu foil

2.2 Measurement Techniques

All experiments were conducted in the ARL's low-pressure strand burner (Fig. 2).[13] The apparatus includes a windowed chamber that is capable of being pressurized to 10 MPa (1,450 psi). Nitrogen (N_2) was employed as the bath gas. To maintain constant pressure, the system includes a ballast tank that adds considerably to the system's overall volume, thus minimizing pressure increases due to propellant combustion. Pressure was measured with a Setra Systems pressure transducer and a Heise mechanical dial gauge. The desired chamber pressure for each experiment was established just before ignition. Ignition was achieved by electrically heating a nichrome wire placed on top of the strand. Events were recorded with a Phantom V7.3 camera equipped with a fixed 50-mm Nikon lens and an aperture setting of f/16. Images were acquired at 100 frames per second with exposure ranging from 3 to 10 µs. To prevent smoke from obscuring the camera's view, a slow, steady stream of N_2 was flowed through the chamber during the burn. Gas flowed from the inlet at the center of the chamber base toward the exhaust port located at the top center of the chamber.

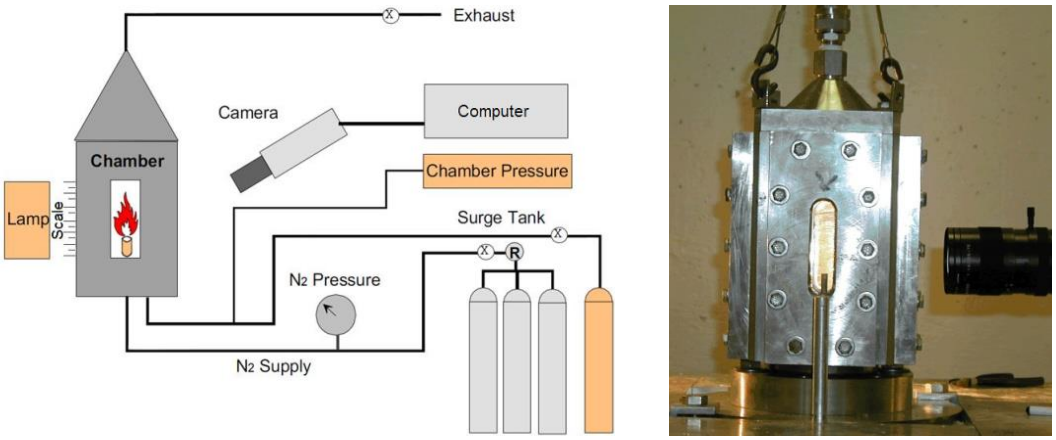

Fig. 2 Schematic of strand-burner facility (left); windowed strand burner (right)

The test articles were burned at a constant pressure in the range of 3.45–8.62 MPa (500–1,250 psi). To obtain BRs, the position of the burning surface was measured as a function of time along the strands' foil-bonded edge. The linear least squares method fits to the data yielded in the BRs. For each sample configuration (pressure, foil type, and foil thickness) 3 tests were performed.

3. Results

3.1 Aluminum Foils

Foil-less sections of JA2 strands burned in cigarette-like fashion, and BRs were easily measured. Once the foil-bounded section was reached, the BR quickly increased along the foil's edge, and the acceleration progressed until a second steady state emerged: with the burning surface being planar, but no longer making a right angle with the bonded edge. This is illustrated in Fig. 3.

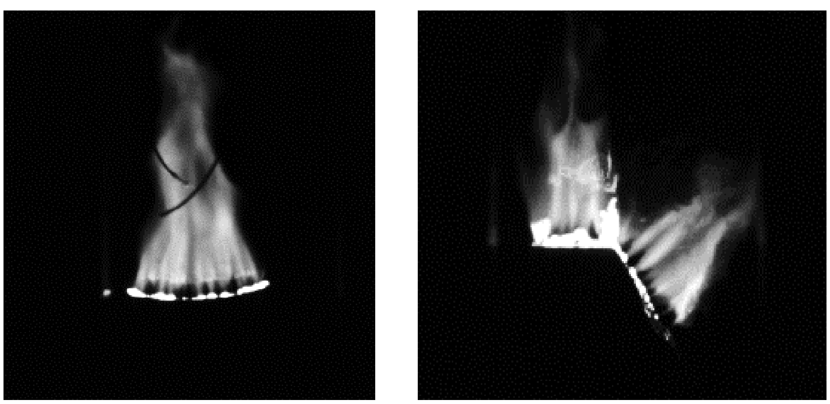

Fig. 3 JA2 flame front with 3-mil Al at 3.51 MPa, prior to (left) and after (right) the foil is reached

The burning of JA2 samples bonded to an aluminum tape of either 2- or 3-mil thickness were recorded. However, the 3-mil tape had a 1-mil-thick adhesive while the 2-mil tape had a 2-mil-thick adhesive, and this difference had a noticeable effect on the results. Initial analysis of the results produced by 1- and 3-mil-thick Al foils suggested that 2-mil Al would produce a burning-rate increase greater than that produced by the 3-mil Al. (It was unknown whether the increase would be greater or less than that produced with 1-mil Al.) However as the data in Fig. 4 show this was not the case. We presume this occurred because the adhesive acts as an insulator, reducing heat transfer from the foil to the propellant. The insulating effect of the adhesive was also observed in the Cu-foil experiments.

Comprehensive shot-by–shot, burning-rate data of the Al-bounded JA2 is provided in the Appendix. Figure 4 provides a graphical summary of the data along with standard power-law function fits to the sets. (The 1-mil Al data are provided from a previous report.[7]) Even with the insulating effects of the adhesive, the presence of the foil produced higher BRs. With the foil attached, burning-rate coefficients ranged from 0.43 to 0.98. Burning-rate exponents were 0.62, regardless of foil thickness.

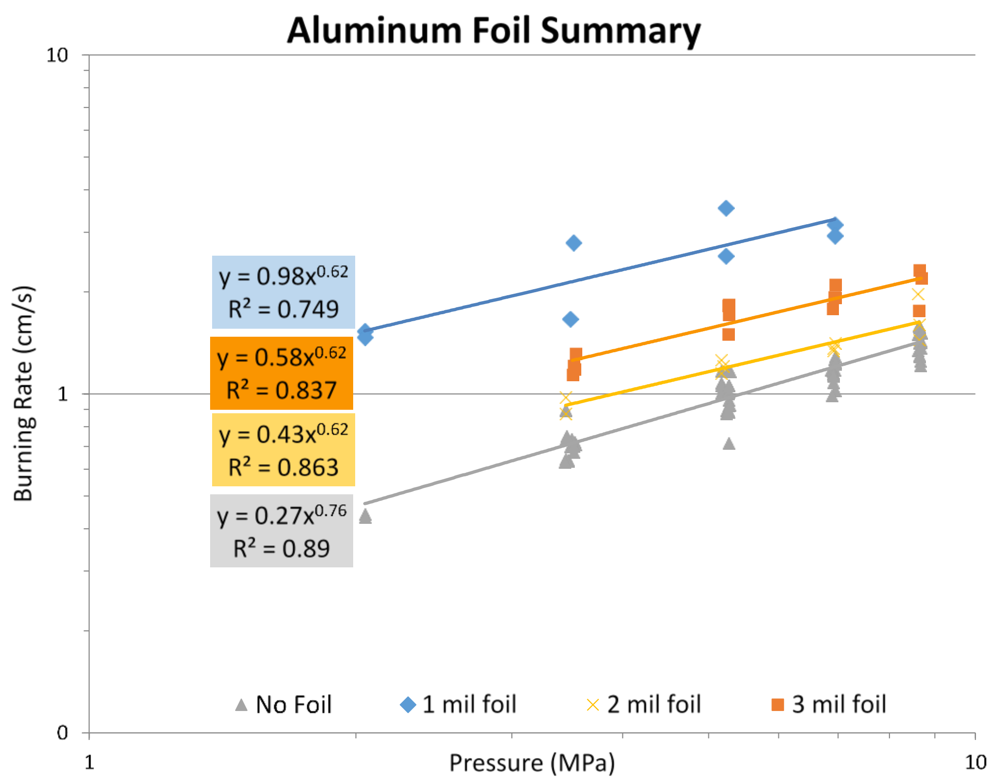

Fig. 4 Summary BR data for JA2 bounded with various thicknesses of Al foil

Another way to evaluate the data is to observe how much of a performance increase is achieved as a function of foil thickness. Burning-rate increases are realized as the heat conducted by the foil goes to preheating the propellant sample; however, the foil also absorbs heat and transfers it to the surrounding atmosphere. As the foil thickness increases from zero, more heat is conducted into the propellant sample. However, as the foil thickness increases further, heat is also conducted away from the propellant at a greater rate. Eventually the heat conducted away from the propellant becomes a detriment to burning-rate enhancement. Consequently, there is an optimum foil thickness that can be pursued that conducts the greatest net energy into the propellant for highest performance gains.

Figure 5 illustrates a portion of this, where the 1-mil-thick foil appears to be an optimized thickness at all pressures. The 2-mil-thick foil should have higher performance increases but is hampered by the thicker adhesive used for the experiments. However, without data to populate the performance increase of more foil thicknesses it is difficult, if not impossible, to determine the true optimized foil thickness.

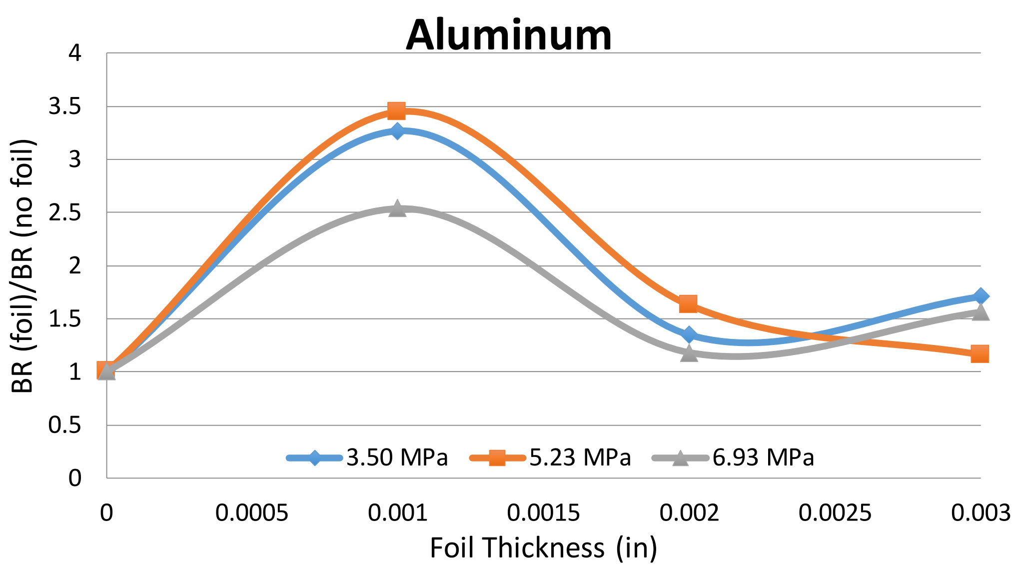

Fig. 5 JA2's BR enhancement based on Al-foil thickness

3.2 Copper Foils

Much like the Al foils, the Cu foils and tape increased the BR of JA2. Figure 6 illustrates the burning of JA2 with a 2-mil Cu. For sample preparation, tapes were preferred. However, only 1.4-mil-thick Cu tape could be obtained from a commercial source. Therefore 2- and 3-mil-thick foils were employed for the other measurements. Employing the acetone-adhesion method on the 2-mil foil proved sufficient; however, the 3-mil foil mechanically peeled from the JA2 during the burning event, resulting in a higher than desirable level of scatter in the measurements. We assume this issue arose because the 3-mil Cu was too thick to be gasified by combustion. This is suggested by Figs. 7 and 8, which present posttest examinations of 2- and 3-mil-thick foils. On the 2-mil-thick Cu foils, a pronounced bead produced by melting is observed. That was not the case on most 3-mil samples. Regardless, heat transfer from the 3-mil Cu foil to the propellant is widely inconsistent from sample to sample and led to the scatter seen in the results. Therefore, the reliability of 3-mil Cu is questionable.

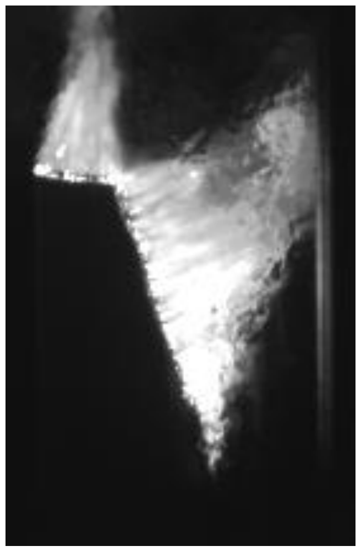

Fig. 6   JA2 with 2-mil Cu foil burning at 8.68 MPa

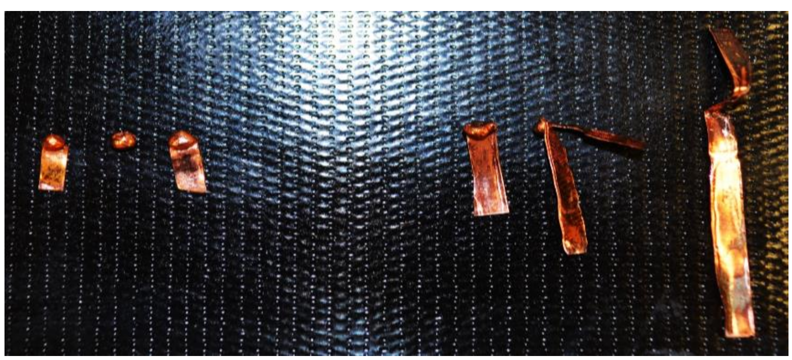

Fig. 7   Copper remains at 6.90 MPa: left is 2-mil Cu, right is 3-mil Cu

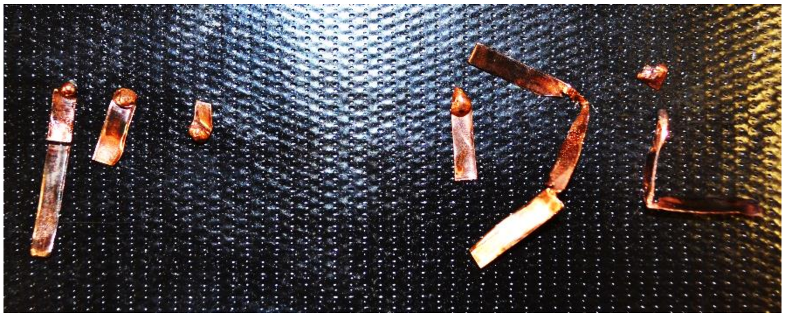

Fig. 8   Copper remains at 8.68 MPa; left is 2-mil Cu, right is 3-mil Cu

A summary of the copper-foil data is shown in Fig. 9, and it illustrates the scatter in the 3-mil foil's data. Burning-rate coefficients ranged from 0.54 to 1.67, while baseline JA2 is only 0.27. As found in the Al foil's data, burning-rate (pressure) exponents decreased slightly from the baseline. However unlike the Al data, exponents of the Cu foil's data continued to decrease with an increase in thickness. This suggests that as foil thickness is increased, the BR of the propellant is less dependent on pressure.

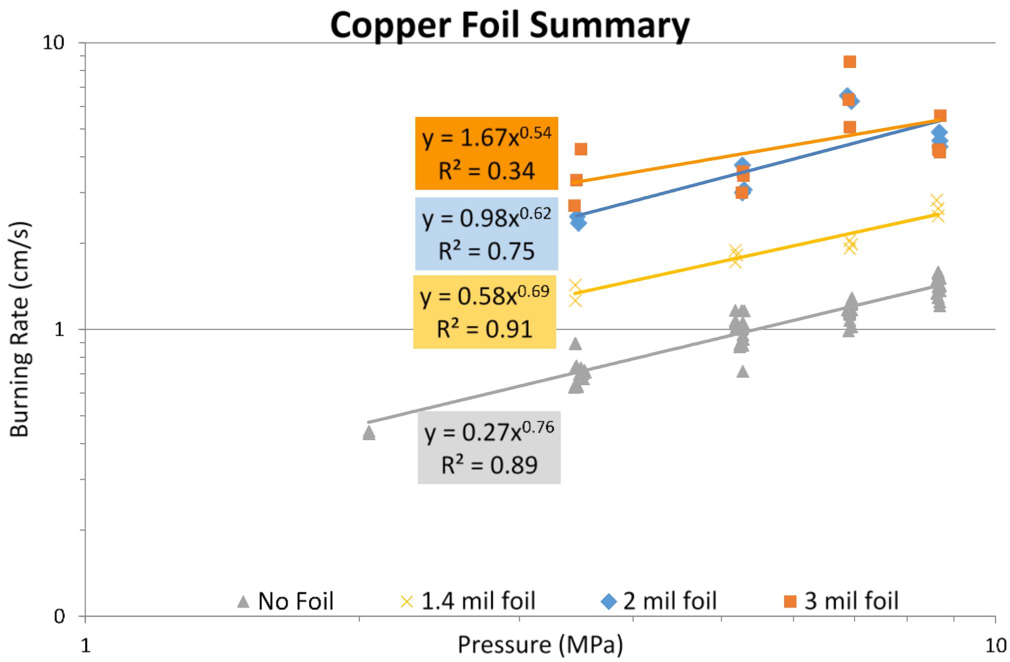

Fig. 9   Summary BR data for JA2 bounded by various thicknesses of Cu foil

Figure 10 illustrates the performance gains realized as a function of copper-foil thickness. We assume that a 1.4-mil-thick Cu foil will increase the BR more than shown if it were bonded to the JA2 sample with acetone rather than the tape's acrylic adhesive. Like the aluminum foil, it is not possible to determine an optimal foil thickness for performance gains without performing experiments on more foil thicknesses.

A short, small sampled side experiment was conducted to provide some insight into the adhesive effects. The study included 3 samples of JA2 in which the samples had a foil adhered with a glue on one side and a foil adhered with acetone on the other. The glue side produced a performance increase of 85%–150% whereas the acetone showed a performance gain of approximately 260%. In order to keep the larger dataset consistent, the glued samples were not included in the data analysis (but the data are provided in Appendix).

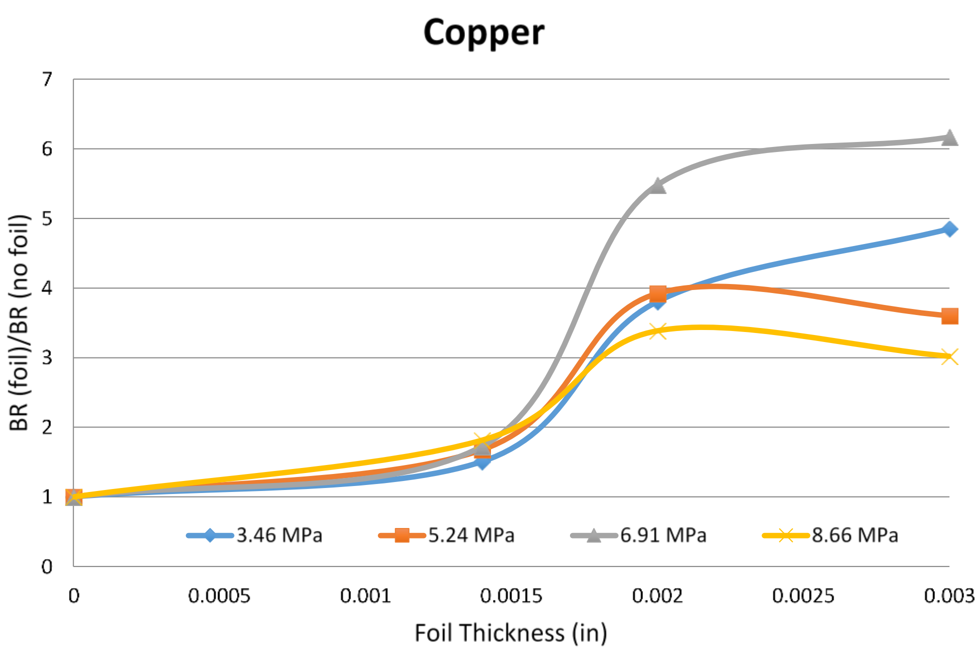

Fig. 10 JA2's BR enhancement based on Cu-foil thicknesses

4. Conclusions

Experiments were conducted to visualize the (constant pressure) deflagration of JA2 strands bounded by either Al or Cu foils. Pressures ranged from 3.45 to 8.62 MPa. Foil thicknesses ranged from 1 to 3 mils. Normal linear-burning rates, BRs adjacent to the strand's side wall, and the angle between the burning surface and the sidewall were measured from video recordings. Considered together, the results indicate the increase in gas (mass) generation rates observed were primarily due to the foils acting as an ignition source that served to propagate a deflagration wave normal to the side wall, increasing the total area of the burning surface. Bonded to Al foils, mass-generation rates increased by as much 350%, and with Cu foils increases up to 500% were observed. We suspect the increase is greater with Cu because its thermal conductivity is higher. It was also observed that the gas-generation rate for foil-bounded strands was less dependent on pressure than the baseline (foil-less) configuration.

Discrepancies noticed during the experiments primarily focused around the adhesion of the foil to the propellant. The type and quality of the foil–propellant adhesive interface made a measureable difference in performance. For samples that employed an acrylic adhesive supplied with the foils (e.g., tapes), the burning-rate enhancements appeared to be reduced when compared to a similar sample adhered with acetone. Likewise, diminished results were also observed when a glue was employed to adhere the foil. In effect, the acrylic adhesive and glue acted as an insulator, diminishing performance gains. This is not surprising as any (nonenergetic) adhesive, no matter how thin, will act as an insulator.

In real-world applications, manufacturing scenarios will almost certainly necessitate an intermediary material between the conductive metal and propellant. Ultimately, this material will alter (most certainly decrease) the effectiveness of the metal in its heat transfer to the propellant. Therefore, it is imperative to account for the material properties of the intermediary material when designing the model to predict performance enhancement of foiled or wired propellants.

Pertaining to a relatively simple geometry, our results provide a solid basis with which to validate computational fluid-dynamics models for simulating the deflagration of wire-embedded propellants. Any further enhancements to the modeling effort beyond the scope of the experiments here will focus on the propellant formulation. If such a time arises, experiments will be conducted to determine the effects of metal wires or foils on that specific propellant formulation.

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Appendix. Shot-by-Shot Summary Data of Pressure (P), Burning Rate (BR), and Cone Angle of Flame (θ)

This appendix appears in its original form, without editorial change.

P	BR, no foil	BR, foil	Increase	Θ	Θ
MPa	cm/s	cm/s	%	Measured	Calculated
			1-mil Al		
6.94	1.18	3.15	168	21	22
6.94	1.22	2.94	140	21-25	25
5.23	0.89	3.54	297	14-17	15
5.23	0.87	2.56	193	20-24	20
3.49	0.70	1.66	138	24-30	25
3.52	0.67	2.80	315	13-15	14
2.05	0.44	1.53	246	16-20	17
2.05	0.43	1.47	238	17	17
			2-mil Al		
3.45	0.64	0.87	36	48	47
3.45	0.74	0.98	33	48	49
5.19	1.04	1.21	16	50	60
5.17	1.01	1.15	15	49	61
5.17	1.08	1.26	17	56	59
8.65	1.41	1.60	13	64	62
8.61	1.49	1.97	32	53	49
8.65	1.30	1.44	11	68	64
6.95	1.02	1.41	38	47	46
6.91	1.15	1.34	17	54	59
6.91	1.15	1.37	19	52	57
			3-mil Al		
3.51	0.72	1.14	59	37	39
3.52	0.70	1.22	73	34	35
5.27	1.06	1.72	62	40	38
5.26	1.17	1.83	57	39	40
6.90	1.17	1.79	53	38-48	41
6.95	1.24	1.93	56	38-47	40
8.64	1.59	1.77	11	51-60	64
8.69	1.51	2.20	45	42	43
3.54	0.71	1.32	85	41	33
3.53	0.72	1.18	64	37	38
5.26	1.00	1.50	50	45	42
5.27	1.01	1.84	82	44	33
6.93	1.26	1.94	53	40	41
6.95	1.29	2.10	63	41	38
8.65	1.41	2.32	64	40	38

P	BR, no foil	BR, foil	Increase	Θ	Θ
MPa	cm/s	cm/s	%	Measured	Calculated
			1.4-mil Cu		
3.45	0.89	1.27	42	26	45
3.45	0.90	1.43	60	35	39
5.19	1.02	1.83	78	31	34
5.17	1.17	1.89	62	30	38
5.17	1.06	1.72	62	36	38
8.65	1.57	2.65	68	36	36
8.61	1.34	2.84	112	28	28
8.65	1.52	2.50	65	32	37
6.95	1.23	1.99	62	27	38
6.91	1.08	1.92	78	32	34
6.91	1.15	2.05	78	33	34
			2-mil Cu		
3.47	0.63	2.48	291	18	15
3.48	0.64	2.36	270	12	16
5.27	0.88	3.01	241	18	17
5.27	0.93	3.76	306	13	14
5.29	0.72	3.08	330	13	13
6.87	1.16	6.56	463	13	10
6.94	1.17	6.26	433	12	11
8.67	1.25	4.89	290	15	15
8.68	1.42	4.35	206	18	19
8.68	1.43	4.57	219	16	18
3.47[a]	0.62	1.75	183	37	21
3.48[a]	0.52	0.97	86	40	32
5.27[a]	0.83	1.49	80	43	34
			3-mil Cu		
5.26	0.89	3.01	237	17	17
5.27	0.96	3.57	272	18	16
5.28	0.93	3.45	272	13	16
6.91	1.14	8.61	657	8	8
6.89	0.99	6.36	542	6	9
6.91	1.13	5.10	351	12	13
8.65	1.29	4.25	229	17	18
8.68	1.37	5.60	309	19	14
8.67	1.21	4.17	243	19	17
3.50	0.74	4.27	480	4	10
3.46	0.75	3.33	344	9	13
3.44	0.63	2.72	331	18	13

[a] The first three 2-mil Cu samples are the same JA2 sample as the last three, respectively. The top three employed acetone to adhere the foil to the JA2 while the last three recordings employed a glue to adhere the foil. This resulted in a noticable difference in performance.

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List of Symbols, Abbreviations, and Acronyms

Al	aluminum
AMRDEC	US Army Missile Research, Development, and Engineering Center
ARL	US Army Research Laboratory
BR	burning rate
CFD	computational fluid dynamics
Cu	copper
N_2	nitrogen gas
P	pressure
θ	theta; cone angle of flame

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